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This report summarizes the results of the panel discussions and presentations from the International Workshop on Structural Health Monitoring held at Stanford University, Sept. 18-20, 1997. Structural health monitoring is an emerging technology which combines advanced sensing technology with a knowledge of material/structural damage characteristics to monitor the condition of structures in real time while in service. Technical presentations made by researchers and experts from industry, academe, and government were divided into several categories: sensing technology development, modeling and diagnostic methods, system integration and applications. Three panel sessions were held separately devoted to discussions of civil infrastructure and aerospace/general applications, current status assessment, technical barriers and research issues, and general concerns. This report provides a status report on the technology and research.

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Structural Health Monitoring:

A Summary Report
on the First Stanford Workshop on Structural Health Monitoring, September 18-20, 1997

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ABSTRACT

This report summarizes the results of the panel discussions and presentations from the International Workshop on Structural Health Monitoring held at Stanford University, Sept. 18-20, 1997. Structural health monitoring is an emerging technology which combines advanced sensing technology with a knowledge of material/structural damage characteristics to monitor the condition of structures in real time while in service.

Technical presentations made by researchers and experts from industry, academe, and government were divided into several categories: sensing technology development, modeling and diagnostic methods, system integration and applications. Three panel sessions were held separately devoted to discussions of civil infrastructure and aerospace/general applications, current status assessment, technical barriers and research issues, and general concerns. The panelists include: Roy Ikegami of Boeing Defense &Space Group, Andrew Ball of British Aerospace, Takis Blanas of the Army Research Laboratory, Charles Sikorsky of California Department of Transportation, Richard Livingston of the Department of Highway Administration, Emin Aktan of Drexel University, and K. Egawa of the Niigata Institute of Technology.

This report starts with the definition of structural health monitoring (SHM) followed by the assessment of potential markets for the applications of the technology. The current technologies available for the technology are evaluated, and the critical research issues related to technology development are listed based on the discussions and presentations from the Workshop. This report intends to provide a status report on SHM technology and needed research issues for technology development.

1 WHAT IS STRUCTURAL HEALTH MONITORING ?

Knowledge of the integrity of in-service structures on a continuous real-time basis is an ultimate objectives for the end users, maintenance crews, as well as manufacturers. With such knowledge, the users can count with confidence on the optimal use of the structures and minimize the downtime and avoid catastrophic failures, while the manufacturers can improve their products, reduce inventory and minimize the cost. However, currently, only limited knowledge can be accumulated in real time through scheduled maintenance or periodic inspections, which require extensive labor, cause downtime, and are expensive.

Recent advances in sensing technologies and material/structural damage characterization combined with current developments in computations and communications have resulted in a significant interest in developing new diagnostic technologies for monitoring the integrity of and for the detection of damage of both existing and new structures in real time with minimum human involvement. Using distributed sensors to monitor the "health" condition of in-service structures becomes feasible if sensor signals can be interpreted accurately to reflect the in-situ condition of the structures through real-time data processing. The entire system could be integrated and automated to perform real time inspection and damage detection.

Therefore, the essence of structural health monitoring (SHM) technology is to develop autonomous systems for the continuous monitoring, inspection, and damage detection of structures with minimum labor involvement. The results of structural conditions could be reported through a local network or to a remote center automatically. Clearly, the development of such systems would involve many disciplines such as structures, materials, computations, signal processing, etc., as shown in Figure 1.

Although some conventional NDE techniques can be considered within the framework of structural health monitoring, there can be a difference in terms of data interpretation between the traditional NDE and SHM. The traditional NDE techniques tend to use direct measurements to determine the physical condition of the structures. No history data is needed. The accuracy of the diagnosis strongly depends upon the resolution of the measurements, which rely heavily on the equipment. However, the SHM techniques would use the change in the measurements at the same location at two different times to identify the condition of the structures. Hence, the history data is crucial for the technique. The accuracy of the identification depends strongly upon the sensitivity of sensors and the interpretation algorithm. Hence, the NDE relies more on the equipment, but the SHM is more dependent upon the interpretation software. Hence, miniaturization is potentially feasible for the SHM techniques.

The potential direct benefits from such systems are enormous such as:

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- Real-time monitoring and reporting - saving in maintenance cost
- Minimum human involvement - reducing labor, downtime, and human error
- Automation– improving safety and reliability

With the reduced downtime and improved reliability, in-service structures could be used more productively with less cost. The increase in the reliability of the structures could translate into an increase in productivity by benefiting from the safe operation of the structures. The indirect benefit from the development of the technology for the society as a whole can be very significant in many sectors of industry.

Smart software　　　　Sensors/actuators

Structures　　　　　　Materials

**Structural Health
Monitoring**

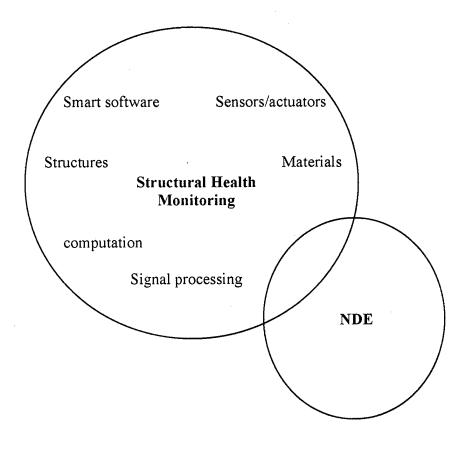computation

Signal processing

NDE

Figure 1 The basic components of structural health monitoring

Typically, such a built-in diagnostic system, in addition to the host structures, would consist of at least two major components: a built-in network of sensors for collecting sensor measurements and software for interpretation of sensor measurements in terms of the physical conditions of the structures. However, depending upon the inputs, the structural diagnostic techniques can be divided into two types: passive sensing systems without known inputs (with sensors only) and active sensing systems with known inputs (with both sensors and transducers [actuators]).

1.1 Passive Sensing Diagnostics

For a passive sensing system, only sensors are installed in the structures. Sensor measurements are constantly taken in real time, while the structures are in service, and are compared with a set of reference (healthy) data. The sensor-based system estimates the condition of the structures based on the data comparison. Hence, the techniques of data comparison for interpretation of structural conditions are crucial for a reliable system. The system would require either a data bank which has a history of pre-stored data or a structural simulator which could generate needed reference data.

Because the input energy to the structures is typically random and unknown, the corresponding sensor measurements reflect the response of the structures to the unknown inputs. This type of diagnostics has been primarily applied to the determination of the unknown inputs which cause the changes in sensor measurements, such as external loads, temperature, pressure, etc.

1.2 Active Sensing Diagnostics

For an active sensing system, known external mechanical or non-mechanical loads are input to the structures through built-in devices such as transducers or actuators. Since the inputs are known, the difference in the local sensor measurements based on the same input is strongly related to a physical change in the structural condition such as the introduction of damage.

2   WHERE IS THE MARKET ?

Nearly all in-service structures require some form of maintenance for monitoring their integrity and health condition to prolong their life span or to prevent catastrophic failure of these structures. The potential applications of the SHM technology are very broad, ranging from aerospace structures to civil infrastructures. Some of the highlights presented and discussed in the Workshop are cited as follows:

Current fail-safe conditions of aircraft structures require a substantial amount of monitoring and inspection. The percentage of aircraft that are being operated beyond their design lives is ever increasing. As of 1993, approximately 51% of the aircraft in the U.S. Air Force inventory were over 15 years old and 44% over 20 years old. Yet, some air-

craft models that have already served NATO for 30 years or more may need to be retained for another two decades. One of the problems with aging aircraft is the rise in time needed for inspection and repair. An example has been given by Sampath [1] that for the EF-11A aircraft, on an average, the man-hours required for scheduled inspection and repair of each aircraft in the depot have risen from about 2200 hours in 1985 to about 8000 hours today. Automated inspection could therefore be of great benefit to an aging aircraft fleet.

A recent study on inspection requirements for a modern fighter aircraft (featuring both metal and composite structures) revealed that an estimated 40 percent plus can be saved on inspection time by utilizing smart structural monitoring systems. The situation is illustrated in the table below:

Inspection type	Current inspection time (% of total)	Estimated potential for smart systems	Time saved (% of total)
Flight line	16	.40	6.5
Scheduled	31	.45	14.0
Unscheduled	16	.10	1.5
Service instructions	37	.60	22.0
	100		44.0

Aircraft structural health monitoring is an essential element for continued safe operation. Both the direct costs of carrying out preventive inspections and the indirect costs associated with interrupted service, however, provide a strong stimulus for cost reduction programs. Numbers being reported by Kudva [2] from estimated values are excess in 35 million dollars per year for a F-18 (assuming 33 hours of flight per aircraft per month and 1000 aircraft fleet) and more than 9 million dollars for a T-38 (based on 420 flight hours per aircraft per year , a 720 aircraft fleet). The automation of just one logistics function could result in an approximate saving of 100,000 dollars per year in manpower and equipment.

Furthermore, the cost for maintaining safe operation of a fleet of spacecraft and a space station in space can be considerably higher than for airplanes and helicopters. For reusable space vehicles such as NASA's single-stage-to-orbit spacecraft, low-cost but highly reliable maintenance is critical for the safety and economical operation of such a fleet. Remote sensing and real-time damage diagnosis are important for the economical and safe operation of these structures.

Aircraft and spacecraft manufacturers and operators have indicated that they would like to see more integrated automated inspection systems provided that they do offer a cost benefit and possibly are more reliable when compared to current inspection methods. They should not interfere with other flight systems and preferably be communicative to maintenance personnel.

Beside health monitoring for helicopters and ground vehicles, health monitoring for missile systems is of major concern to the U.S. Army. One of the most widely used techniques to monitor the structural health of rocket motorcases and propellant depends on either taking the missile out of stock and conducting static firings or actually dissecting the motorcases, nozzles, and propellant and conducting structural integrity tests. The tests include dog bone tension test specimens and specially configured nozzle test specimens. This approach to determining the structural health and shelf-life of missile systems is very time-consuming, expensive, and represents only a small sample of the inventory.

Health monitoring of civil infrastructure systems is cost-effective and necessary since these systems are generally the most expensive investments/assets in any country. In the U.S. assets are estimated at $20 trillion. In addition, these systems have long service lives compared with any kinds of commercial product, and are rarely replaceable once they are erected.

Since civil infrastructures are huge in size compared to any other structures and are exposed to harsh environments at all times, maintenance and damage inspection of civil infrastructures can be costly and time-consuming. Any downtime could cause a much more significant economic impact on the society than downtime with any other types of structures. Furthermore, these structures are susceptible to natural disasters such as earthquakes and hurricanes. For critical structures, such as hospitals, fire stations, military control/surveillance centers, major bridges, power stations, and water treatment plants, it is imperative that their health be assessed immediately after a major catastrophic event. In many instances, the impending collapse of a structure may not be visible from the exterior of the structure. During the January 17, 1994, Northridge, California earthquake several structures that were weakened (but undetected) by the main shock collapsed when a major aftershock occurred. Thus, identification of critically damaged structures will enable timely evacuation of occupants.

3 RESEARCH ISSUES

In general, the structural health monitoring system would include five major parts: sensing technology, diagnostic signal generation, signal processing, identification and interpretation, and integration.

3.1 Sensing Technology

Many sensors available in the market or still being developed such as fiber optics, dielectric measurement sensors, piezoelectric materials, strain gages, MEMS sensors, can be used for applications for health monitoring purposes. Fiber optics sensors have found applications ranging from civil infrastructures to aircraft structures [1]. Piezoelectric materials were used as both sensors for measurements and actuators for generating diagnostic signals for monitoring damage in structures made of both metals and composites [1]. A peak strain sensor was presented for the damage assessment of bridges and buildings [1].

For active sensing diagnostic systems, the source of excitations can be categorized into two types: mechanical load and thermal load. Piezoelectric materials and rheological fluids have been demonstrated to be effective means for generating local- or global-based excitations, respectively [1]. Laser has been used to generate ultrasonic waves in structures [1].

Although there are a variety of sensors available in the market, they may not be readily applicable to monitoring the condition of large continuous structures. A network of distributed reliable and economical sensors is required. Accordingly, key technology issues in the sensing are as follows:

- **Distributed sensors:** Techniques will need to be developed to distribute a large array of sensors in a network economically and effectively. This area is particular important for civil infrastructures, because these structures are typically large.

- **Remote sensing:** Wireless communication between local sensors and a controller is needed. As the number of sensors increases with the size of the structures, so does the number of communication wires. The management and handling of hundreds and thousands of wires can be difficult and challenging. With remote sensing capability, data could be gathered locally, but the structures could be monitored remotely.

- **Sensor reliability and integrity:** The failure of sensors or actuators may result in fault signals or make the systems useless. The integrity of sensors and actuators under various loading conditions and environments for particular applications needs to be studied. The long-term behavior of sensors and actuators and the interfacial strength between the sensors/actuators and the host structures need also to be considered.

3.2 Diagnostic Signal Generation

For passive sensing systems, sensors measure the response of the structures in response to unknown external thermal, mechanical, or chemical loads. These mechanical or non-mechanical loads are unknown and need to be determined. However, for active sensing systems, additional signals are measured by the sensors in response to the excitation generated by built-in actuators or transducers in a controlled environment.

These controlled diagnostic signals are used to excite the sensor measurements for interrogation of the local abnormal behavior of the structures. Accordingly, the determination of the diagnostic signals and generation would critically affect the measurements and affect the identification. Piezoelectric materials have been typically used as actuators to generate diagnostic signals [1].

Research issues:

- **Size and power of signal generator**: There are very limited built-in actuators available in the market for structural health monitoring. The actuators must be small enough to be built into the structures, but must be powerful enough to generate diagnostic signals for neighboring sensors. The power transmission between the built-in actuators and the hosting structure must be fully understood.

- **Diagnostic signal selection**: The diagnostic signals must be controllable, repeatable, reliable, and be sensitive to the damage, defects, or anomaly of particular concern. The relationship between the input signals and particular damage or defects is important for determining the type of the diagnostic signals.

3.3 Signal Processing

The data retrieved directly from sensors contain a lot of information, most of which are unusable and irrelevant to the interest of the particular concern. Furthermore, the data can be highly corrupted by the environment and noise, resulting in difficulties in interpretation.

Research issues:

- **Signal presentation**: Raw sensor measurements need to be processed before they can be used for interpretation. Signal processing is crucial because the processed data will be used to identify the condition of the structures. Efficient and good processing techniques could make the interpretation easier, faster, and more accurate.

- **Sensor calibration**: Confidence in sensor measurement uniformity is needed. Sensor measurements can be affected by the properties of the interface between the host structures and the sensors. For distributed sensors, each sensor can produce different outputs for the same given input.

3.4 Damage Interpretation/Identification Analysis

The damage detection/identification analysis plays a major role in the health monitoring system and can be regarded as the "brain" of the system. The accuracy and reliability of the system strongly rely upon the accuracy and reliability of the analysis for relating the sensor measurements to the physical changes in the structures. Sensor measurements are point-wise in the continuous structures. Damage or an abnormal condition may not appear at the location where the sensor is located. Therefore, sensor information needs to be extrapolated for prediction of damage that appears at a distance away from the sensor locations. Furthermore, there are many factors could influence the sensor measurements beside the particular defects. Hence, it becomes very difficult to interpret the sensor measurements in terms of physical condition of the structures.

Mathematically speaking, determination of the physical condition of a structure based on sensor measurements is a nonlinear inverse problem. Several numerical and analytical techniques have been proposed or adopted for the proposed applications [xx]. Modal

analyses, system identification, neural network algorithms, generic algorithms, optimization algorithms, etc., have shown some promising results. However, most results are limited to laboratory control environments and on simple structural configurations. In practice, most techniques require an extensive amount of history data of the structures in both undamaged and damage conditions, which is very difficult to obtain experimentally and analytically from the actual structures.

Issues:

- **Damage diagnosis:** Novel identification or interpretation algorithms are critically needed to relate the sensor measurements to the physical conditions of the structures in terms of damage and defects.

- **Computation:** Accurate and fast computational techniques are needed for the efficient and effective modeling of large structural components. Current finite element techniques require considerable computational time for large-scaled structures.

- **Damage characterization:** The relationship between damage or defects and the measurable physical quantity of the structure near the damage needs to be established.

3.5   System Integration

Integration of the system involves both hardware and software. The final system must be reliable. It does not take too many fault calls to ignore the system. Green, yellow, and red lights would be the ideal output for the system. Green indicates the healthy condition of the structure and a red light implies an unsafe condition of the structures. The yellow light provides an indication that there exist concerns about the structural health condition. Service may be needed. The more information that can be display at the yellow light, the better the system would be. The yellow light is the most challenging and difficult in the development of the system.

Issues:

- **Structural integrity:** It is a general concern that inclusion of sensors and actuators as a part of the structures may influence the mechanical properties and/or performance of the structures. Such influence should be minimized as much as possible if not avoided.

- **User interface:** The system must be made to be easy to use. It would be desirable that the proposed system could display through its initial interrogation the condition of the structures in one of the three color lights: green (safe to use), yellow (use with caution, needs inspection), and red (unsafe, not to use). More detailed information regarding the structural condition could be obtained if further interrogation is needed.

- **System miniaturization:** The entire system should be miniaturized to occupy as little space as possible. Since the proposed system will heavily rely on software, miniaturization of the entire system is feasible.

4 CONCLUSION

Structural health monitoring is an emerging technology. Successful development and implementation of the technology could lead to reduction in costs associated with maintenance, minimization of downtime avoiding unnecessary economic loss, and improvement of the safe use of structures. The economic saving in both military and nonmilitary sectors as a whole can be enormous. However, there exist several technical issues that need to be overcome before the technology can be widely adopted and accepted.